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Lower Quadrangular Frame Beams of the Church of the Transfiguration on Kizhi Island, Russia

Renowacja belek dolnej czworokątnej ramy konstrukcyjnej cerkwi Przemienienia Pańskiego na wyspie Kiży w Rosji

Słowa kluczowe: architektura drewniana, dolna rama czworokątna, wzmacnianie belek, inżynieria wzmacniania

Key words: wooden architecture, lower quadrangular frame, beam strengthening, engineering strengthening

1. INTRODUCTION

Most wooden architecture monuments are to be found in Russia. This architectural style is considered to be part of our common heritage. According to researchers, there are approx. 30 similar architectural complexes in Russia. There are also similar monuments abroad, but they are fewer in number. The majority of them are to be found in Ukraine and Poland, but also in Armenia, Belorussia, Bulgaria, Germany, Romania, the Czech Republic, Baltic states, and Scandinavia. The oldest wooden buildings to be found outside of Russia include the Urnes Stave Church built in 1150 in Norway and the Church of the Assumption of Holy Mary and St. Michael the Archangel built in 1388 in Haczów, Poland. But from the point of view of engineering solutions, the most famous and unique monument is located on Kizhi island on Onega Lake.

In Russia, the risk of losing wooden architecture monuments altogether increases each year. The cultural heritage is of global renown, but is literally fragile and under threat (Permilovskaya AB, 1990; Milchik MI, 1999). On average, at least ten wooden architecture monuments are lost each year. One of the reasons for this lies in the lack of engineering solutions in many restoration projects, which are usually based on the ideas, tastes and preferences of those undertaking restoration work.

Currently, Kizhi Pogost is the only preserved Russian complex that includes two multi-dome wooden churches. One of the pearls of Russian wooden architecture is the Church of the Transfiguration that celebrated 300 years of existence in 2014.

2. KIZHI POGOST

2.1. Historical reference

Kizhi Pogost (Fig. 1) has its origins in the beginning of the 15th century. The island is on Onega Lake, which lies 68 km from the capital of Karelia, Petrozavodsk. It is at the centre of a scenic group of small islands called Kizhi skerry. In the late 15th century there were 14 villages on the island (Averyanova EV, 2006). Only two of them have survived – Yamka and Vasilyevo. Both lie in the central part of the island. The villages form part of the Kizhi open-air museum. Yamka village is located on the east bank. It is one of the historical settlements (first mentioned in documents dated 1563). Today, a museum village is to be found on the site of the old settlement. Most of the buildings were brought from

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Fig. 1. Kizhi Pogost

different villages of Zaonezhye. Vasilyevo village is located on the west bank. Unlike Yamka, Vasilyevo village has always been small and comprised of no more than 3 houses like most villages of Zaonezhye. The museum located at the old settlement site is a reconstruction of a Zaonezhye village dating back to the late 19th century and the beginning of the 20th century.

The Pogost on Kizhi island has been a museum for approx. 65 years – starting as a church museum (1929) and becoming a federal state cultural institution, ranked as the most important among Russian museums. The Kizhi architectural complex was included in the UNESCO World Heritage list at the World Heritage session held in Banff in Canada on 12th December 1990.

The Church of the Transfiguration is exceptional from the point of view of architectural planning and engineering solutions. There are no equivalents in the world of wooden architecture (Bech-Andersen J, 2005). The Church of the Transfiguration was used for church services during summer, serving the whole parish. According to tree-ring analysis, the church was built after 1713–1714.

The cruciform floor-plan of the church is formed by a central octagonal log structure with four two-tier side annexes facing the four cardinal points. The nave is connected on both sides to a monastery refectory which, in turn, is connected to a porch with two staircases on its western side. The central dome of the Church of the Transfiguration is 37 metres high. This makes the church a unique example of a complete multi-tiered, multi-dome building structure (a masterpiece of a complete multi-tiered, multi-dome structure, Fig. 2).

2.2. Structure of the church building

The main construction tool was the axe. The whole church building structure was completed without using a single nail. The main units and details, as well as the flat ends of logs were cut from wood to provide better waterproofing. Only the ploughshares on the heads were fastened with wrought nails. The drainage system and the roof architectural form were designed in a way which guaranteed water protection, providing safety and longevity to the church building structure. (Pishchik II, 1990).

Structurally, the church was built as a quadrangle on an octagonal base scheme and vice versa. The main body of the building was formed out of three octagonal bases and three quadrangles. The logs forming the

Fig. 2. The Church of the Transfiguration

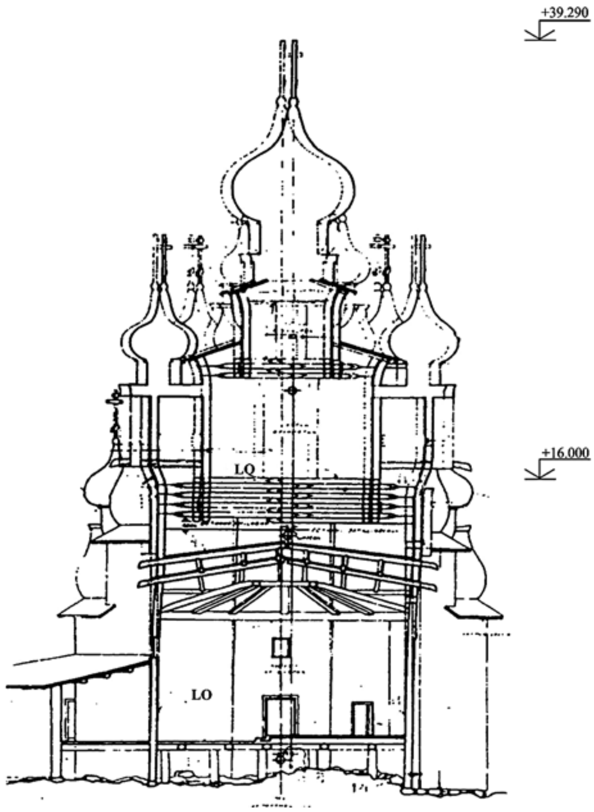

Fig. 3. Lower beam location in the main body of the church building

largest in size – lower quadrangle comprising a 9.5 m bay were cut into the octagonal base panels «v rezh» (a thinned joint — a type of joint, in which logs are not joined together tightly but are connected only in the corners). Orthogonal logs are passed through the gaps between logs arranged in the same direction to form a beam-and-girder structure, in which every square side is 7.5 m in size. Every beam in the lower quadrangle consists of five logs joined together with short vertical ridge-poles, with each one connecting to the next middle octagonal base support. Support is provided at a height of 16 m. The distance from the top of the main body of the building to the highest point of the central dome is 19 m (Fig. 3).

2.3. First restoration attempts

All wooden structures age and demand renovation over time (Charles FWB, 1984; Larsen KE, 2009; 10, Weaver M, 1993). As one of the oldest structures, the Church of the Transfiguration was recognized as being in need of engineering work. The first restoration of the Church of the Transfiguration was carried out in 1949–1959 and later in 1964–1965, but in 1968 the building structure was acknowledged to be under threat (Averyanova EV, 2006).

In 1969, research and development institutions, the Department of Wooden and Plastic Structures (Leningrad Institute of Structural Engineering) and other organizations came together under the supervision of S.A. Dushechkin to work out ways of engineering strengthening of the monument (Gushchina VA, 2004). The church silhouette was hidden behind open-work external scaffolding on several occasions, but the interior structures and the functional purpose of the monument were preserved.

Following a design competition, the decision was made to place a supporting metal frame inside the monument, causing damage to the hard floor-disk which had played a critical structural role for the broken circles of the lower octagonal base crowns. As a result, the church was closed for parishioners. The walls were strengthened with vertically oriented bars with bolts. For over 30 years the church has been supported on this frame.

Recommendations concerning restoration of the Church of the Transfiguration were approved at the 31st session of the UNESCO World Heritage Committee held in New Zealand in July 2007.* This involved approval of decision No. 1137 dated 10.04.2007 of the Chairman of the Government of the Russian Federation, concerning the initiative of the Ministry of Culture of the Russian Federation and the Government of the Republic of Karelia to take measures to safeguard Kizhi Pogost in the period 2008–2014. An organizing committee was established.

In 2008, the Government of the Russian Federation issued Executive Order No. 1633-r dated 11.07.2008 concerning funding of restoration work. Andrew Pouter (Canada), a UNESCO specialist and ICOMOS expert, commented that the project to restore the Church of the Transfiguration was the most complicated in the history of wooden architecture restoration (Dobrynina E, 2011, fig. 4, 5).

Fig. 4. The Church of the Transfiguration (April 2012)

Fig. 5. The Church of the Transfiguration (July 2015)

* United Nations Educational, Scientific and Cultural Organisation; Convention concerning the protection of the world cultural an natural heritage; World Heritage Committee; Thirty-first session; Christch-

urch, New Zealand; 23 June-2 July 2007; Decisions Adopted at the 31st session of the WHC (Christchurch, 2007); WHC-07/31.COM/24; Paris, 31 July 2007

3. EXAMPLES OF LOWER QUADRANGLE BEAM REINFORCEMENT BY L.A. NOVOZHILOV

A detailed engineering survey of the Church of the Transfiguration was carried out by L.A. Novozhilov in the last few years (Novozhilov LA, 2009). He was the first to bring together all the restoration problems of the Church of the Transfiguration into a single coherent concept. He measured deflection of the main beams, identified uneven settlement of various parts of the structure and vertical deviation of the monument. He calculated the basic mechanical properties of the monument' s original wood and identified dangerous cuts of the log crowns which had lost their bearing capability through splicing during replacement of damaged parts during previous restorations. He also found weakening of the basement level beams and of other structural elements, which had resulted from installation of the temporary steel frame.

Lower quadrangle beam reinforcement was necessary to ensure stiffness rather than strength. The maximum deflection of the beams measured not 1/250 but 1/66 of the bay, which excluded them from continued use according to the condition of the second limit state. The deflection on the leeward side of the prevailing wind direction can be a determining factor in the vertical deflection of the monument.

L.A. Novozhilov offered three options for reinforcing the lower quadrangle beams. All of them involve converting the individual lower logs into a form of a truss system (Fig. 6). Such strengthening schemes, especially those which involve transferring forces from the end truss rod girths to beam ends, are generally accepted in stable temperature and humidity conditions. However, given the harsh lake conditions in this particular case, they are questionable and may even be judged to be unacceptable.

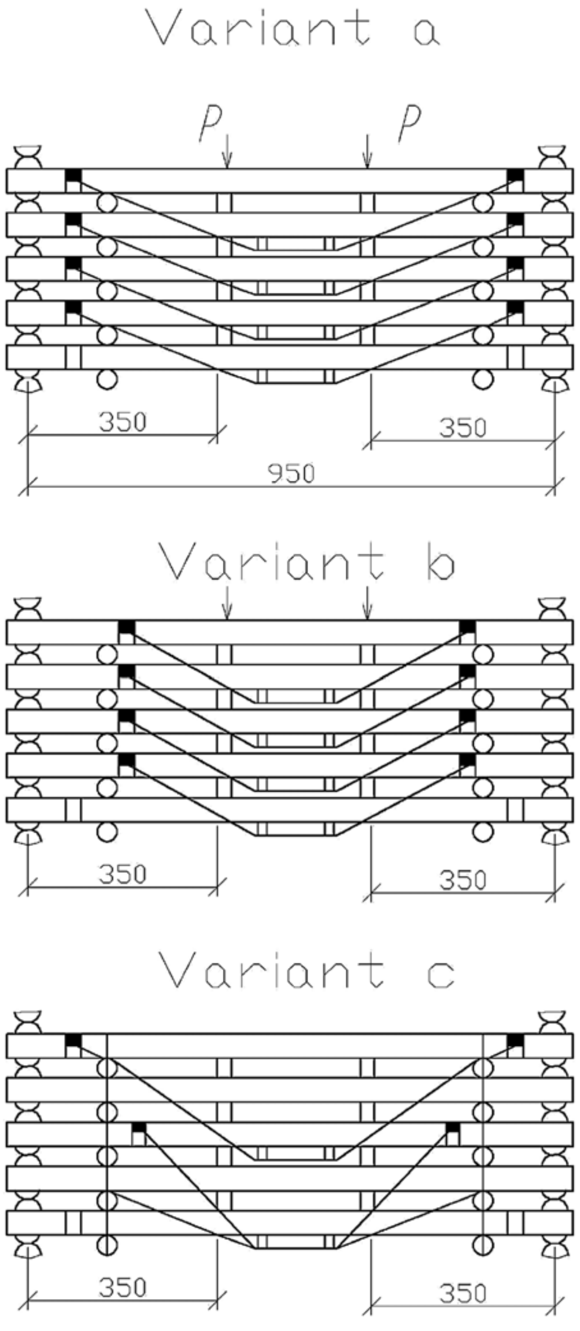

Fig. 6. Lower beam strengthening schemes according to L.A. Novozhilov

4. CLIMATE CONDITIONS ON KIZHI ISLAND

Wood and metal react differently to humidity and temperature: wood swells when wet, but steel does not change in size. In contrast, when temperature changes, the size of wooden elements remains stable, but steel deforms noticeably, especially in the case of long rods. Humidity in the lake environment may reach 100%. Wooden structures undergo long cooling in winter and uneven heating in summer. For example in 2010, it was incredibly hot on the island. In July, day temperature reached 30 °C and more. In September, it was also quite hot. But in winter, severe frosts are to be expected. The temperature range is 50 – 60° C. Thus, the length of the truss girths can change by approximately 8 mm. Daily temperature variations, uneven unilateral heating, intense wood humidification and drying (often under extreme wind loading), and other climate factors make for severe conditions in the face of which the structural integrity of the monument must be maintained. It is also important to note that the island itself is composed primarily of shungite which is an almost black mineral that heats easily. Thus, using long metal parts for strengthening may destabilize the monument through thermal deformation. The bendable beam logs may become compressed and bend. In addition, the transfer of large concentrated stress directly to the old and weakened existing logs and not to their flat ends may result in localized loosening and risk of wood chipping and collapse of the structure. This is because the places of abutment of the girth trussing rods are half a metre or more distant from the flat log ends.

5. PROPOSED STRENGTHENING OPTIONS

As discussed above, several options can be considered for lower beams strengthening in ways that do not change their structural performance. In addition, UNESCO requirements and the principle of authenticity must also be taken into account.

The first and the easiest option is to replace the short vertical ridge-poles between the lower crowns with long log timber gaskets without shear pull perception. In such a log system, only the straps are set to ensure all elements are held in permanent positions. The risk of loss of short ridge-poles is eliminated altogether and instead of five separate logs each beam contains nine logs. If the functional inclusion of four pads (k=0.8) is incomplete, the moment of inertia of each lower beam will increase about 1.6 times.

In the second option, the long log pads fill only two gaps – one between the two upper logs and the other one between the two lower logs, thus ensuring their behaviour is compatible. The middle one, which is the fifth, is still free to be connected to the short ridge-poles in line with the original solution. Thus, each lower "wall" has two three-log beams acting as connections and based on the beam types proposed by V.S. Derevyagina (beams on false tongues). In contrast to well-known bars on false tongues with weakening kerfs, the joint behavior of the three-log scheme provides strengthening not by the pull of the false tongues (UNESCO forbids the use of glues), but by channeling the main tensile stress through stretching. The metal bolts do not exceed 65 cm in length. They are protected from temperature extremes by the wood, and so do not weaken the log edges in edge joints. As a result, they do not distort the original structure of the monument. In this case, the principle of a string set along the principal tensile stresses is implemented.

Calculations show that the perception of principal tensile stresses (σ_1) at the upper seam of the rectangular beam, equivalent to a three-log beam, is provided with ten pairs of long screws of a new generation of L = 500 mm (5 pairs in support zones with 500 mm pitch). If the diameter of the holes is 10 mm, this will not weaken the logs. The average tilt angle of the screw setting in the upper seam is 60°. In the bottom seam, the average operating angle σ_1 must be half as large, i.e. 30°. Screws of the same diameter must be 650 mm long. σ_1 in the equivalent beam below the neutral layer is substantially larger than in the top seam, so that the number of screw-pairs must be increased to 38, i.e. 19 pairs in each of the support zones. Based on this second option, the stiffness of the lower beams will be increased by almost 10 times (Serov EN, 2013). But such a large increase in beam stiffness is not necessary.

The third option is recommended as the most viable. This involves strengthening the lower beams by forming two-log beams while preserving three separate logs (Fig. 7).

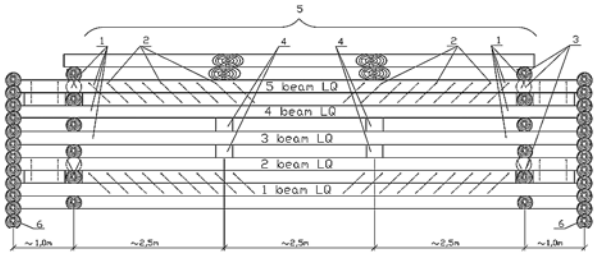

Fig. 7. Composite two-log beams on screwed tie-bars, strengthening the lower quadrangle beams (pos.1) consisting of five separate logs cut "v rezh" (thinned joint): 2 – bolts in the direction of main tensile stresses of equivalent flitch beam; 3 – bolt orientation in log cross sections; 4 — original ridge-poles between lower logs; 5 – middle octagonal base; 6 – lower octagonal base

At the same time, the stiffness of each original lower beam will be increased by 2.36 times, which should be quite sufficient as deflections over 300 years have not exceeded the limit. In addition, the main strengthening will require a total of 128 pairs of screws of the geometry described above. Overall effort as well as complexity of the reinforcing system will be significantly decreased.

Naturally, each of the three strengthening options is related to some challenges. In the truss scheme, problems are related to applying more concentrated loads at the node points of the logs, especially the original ones that have been loaded for three hundred years and have a design resistance to crushing across grain and chipping of, respectively, 1.2 and 1.1 MPa (Novozhilov, 2009). Problems are also related to the selection and fitting of new straight logs, which have been air dried in the "Plotnitsky Center" and have a greater reinforcing capability. Local irregularities of the logs must be removed, not only along the grain. Perhaps, they should be cut as well. We believe these difficulties are surmountable, especially given the fact that the restoration specialists are highly qualified and treat the monument with great care.

6. CONCLUSION

I.K. Rasha, who is responsible for engineering issues in the Church restoration, has opted for the strengthening option suggested by L.A. Novozhilov. Instead of a metal girth, he decided to use thrusts made of LVL, laminated veneer lumber, made of one-way scale wood, and to concentrate the transfer of the tensile force onto a single bolt of more than 40mm in diameter, thus disregarding a fundamental rule of construction, i.e. the principle of divisibility. Experts from Germany have suggested strengthening the lower beams by trimming the log sides with veneer. In our view, beam strengthening with sheets of any compliant material may be only a temporary measure, as the veneer sheets are limited in size. This option is not the best one if one considers other criteria, including UNESCO requirements.

An independent commission of the Ministry of Culture of the Russian Federation is needed urgently to oversee the preservation of the world famous and unique monument of wooden architecture and the selection of the most rational way of ensuring its structural reinforcement.

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Abstract

The paper describes a comprehensive conservation renovation initiated in 2008 on a unique Russian wooden architecture heritage building – the Orthodox Church of the Transfiguration on the island of Kizhi in Russia. For the purposes of renovation, the 300-year old structure was divided into 7 tiers. Conservation work is currently being carried out on the third and fourth tiers. The paper presents inter alia: possible options for changing and strengthening the lower beams of the quadrangular frame, constituting the building structure, which have recently been removed.

Streszczenie

W artykule przedstawiono kompleksowy remont konserwatorski zapoczątkowany w 2008 roku w unikalnym na skalę światową zabytku drewnianej architektury rosyjskiej, czyli cerkwi Przemienienia na wyspie Kiży w Rosji. Podczas prac ta ponad 300-letnia konstrukcja została podzielona na 7 kondygnacji. Obecnie prace konserwatorskie odbywają się na trzeciej i czwartej kondygnacji. W artykule przedstawiono m.in. możliwe warianty wymiany i wzmocnienia niedawno usuniętych dolnych belek czworokątnej ramy tworzącej konstrukcję obiektu.